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0.94-Meter (37-Inch) Cryogenic Demonstration Tank

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ABSTRACT

This paper presents the design, analysis, fabrication, and testing of a 940 mm (37-inch) diameter by 1,118 mm (44-inch) long cryogenic demonstration tank that was developed and manufactured under a contract for SRS Technologies of Huntsville, Alabama. The objective of this program was to develop a lightweight, high stiffness, composite cryogenic tank to store liquid hydrogen for solar thermal propulsion motors. The unique feature of the composite tank is the ultra-thin aluminum liner. The design features, analysis methods, fabrication, and testing of the tank are presented. Design features include the liner, composite tank, polar boss and end closures.

KEY WORDS: Applications-Space, Carbon Fiber, Composite Structures, Design, Filament Winding, Finite Element Analysis, Sealing

1. INTRODUCTION

Lightweight tanks to store cryogenic hydrogen are important components of spacecraft upper-stages, single stage to orbit vehicles, and solar thermal propulsion systems[1]. Figure 1 shows a view of the cryogenic propellant tank incorporated in a Solar Thermal Upper Stage concept proposed by the Air Force Research Laboratory, Edwards Air Force Base, CA[2].

A composite cryogenic tank utilizing current 940 mm (37-inch) rocket motor case tooling was designed, fabricated, and tested at Thiokol Propulsion. The tank used an ultra-thin laminated aluminum foil liner. The composite case was fabricated using M30S/TCR™ prepreg. The polar bosses and cover plates were fabricated using low thermal expansion metal. Figure 2 shows a photograph of the tank after fabrication.

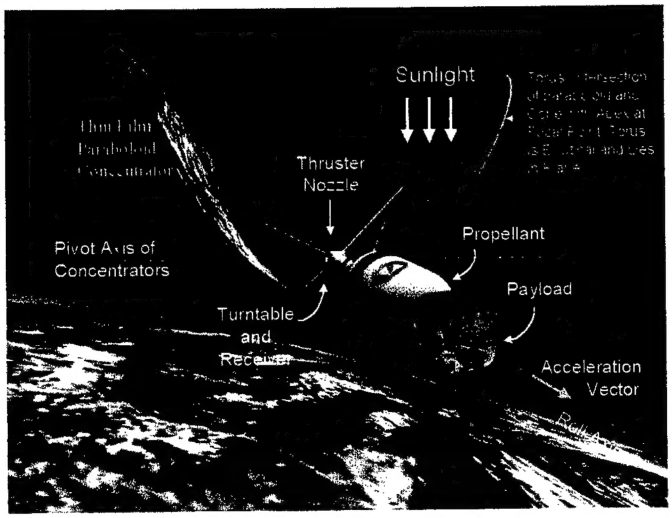

Figure 1. Solar Thermal Propulsion Rocket AFRL

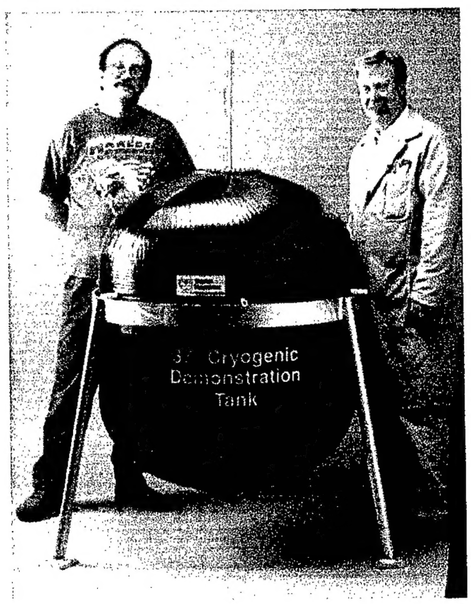

Figure 2. 37" Cryogenic Demonstration Tank

The ultra-thin liner was laid up on a sand mandrel formed with 940 mm (37-inch) case tooling. The mandrel was machined to dimensions developed during the design phase of this project. The composite case was fabricated using polar and hoop windings. The polar bosses were wound into the case during the winding operations. The sand mandrel was removed by washing it out with water after the composite material was cured.

Cover plates were fabricated from the same metal as the polar boss to match the thermal expansion. A cryogenic seal was used to attach the cover plate to the polar boss.

The tank was subjected to three tests at Thiokol. The first test was a pressure test at ambient temperature to verify the tank structure and look for leaks. The second test was a cold shock test where liquid nitrogen was placed in the tank unpressurized and visually inspected for

leaks. The third test was a repeat of the pressure test and leak inspection to verify the cold shock did not damage the tank. No leaks were observed in any of the tests and the tank has been shipped to SRS Technologies in Huntsville, Alabama for further testing using liquid hydrogen at NASA Marshal Space Flight Center.

2. DESIGN

The 940 mm (37-inch) cryogenic demonstration tank was designed and fabricated for LH_2 propellant storage. LH_2 is a cryogenic fluid that has a temperature of 20.K (-432.F) and is stored at a service pressure of 0.345 MPa (50 psig). The main requirement was a minimal weight storage tank with a factor of safety of 2.0 on service pressure.

The tank structure was designed using M30S/TCR™ prepreg composite and metallic end closures. An ultra-thin aluminum liner was fabricated using layers of aluminum foil bonded together with an epoxy material.

The composite over wrap was M30S/UF3339-95 TCR™ prepreg fiber. The UF3339-95 resin was chosen because of the high elongation properties at low temperatures. T300 woven carbon cloth was also used to provide support for the support posts. It was impregnated with UF3339-95 TCR™ resin to bond to the composite over wrap. Metallic polar bosses and end closures were used for ports into the tank. Fill and vent tubes were passed through one cover plate to service the tank.

Initial sizing of the tank cylindrical wall was completed using composite laminate theory. The main focus of analysis was to select the layup of the composite that limited the cross-ply strain to below a experienced crazing limit.

The dome contour was calculated using Thiokol's internal computer program SGA-06. This program calculates an elliptical-type dome profile given dome parameters. Preliminary composite thickness, wind angles, and closed form stress/strain values were also calculated. The dome profile was used to specify the shape of the sand mandrel.

The dome profile was input into another Thiokol in-house computer program, F-wind, to calculate the dome thickness, composite angles and output a finite element model to be used with the commercial computer program ABAQUS. This program also output winding programs for the winding machines at Thiokol. Figure 3 shows a view of the 2D axisymmetric finite element (FEM) model, and Figure 4 shows the tip region of the polar boss, liner, and resin.

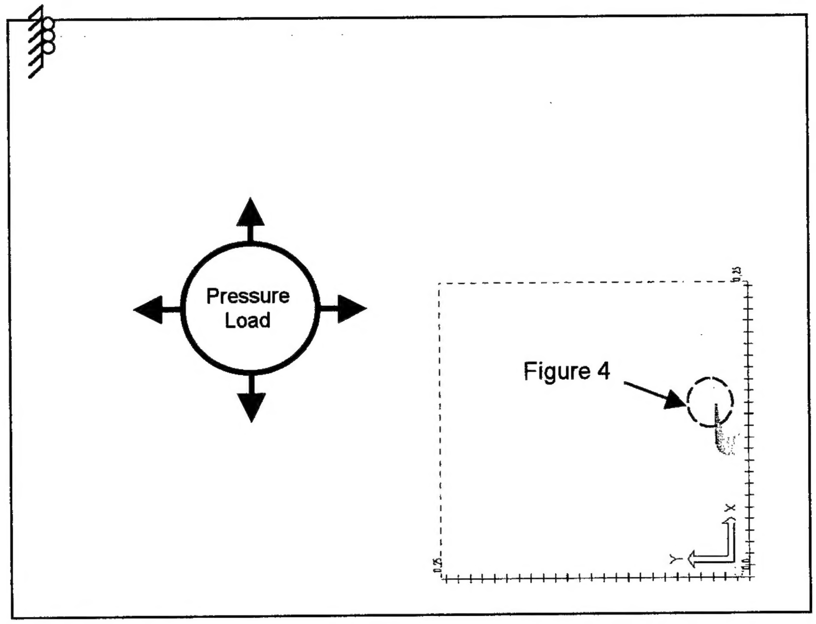

Figure 3. 2D Axisymmetric Finite Element Model

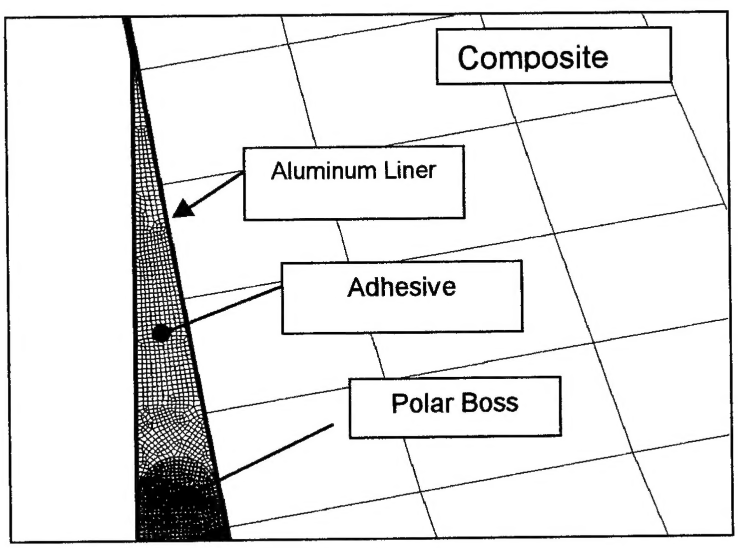

Figure 4. Case Structure Interfaces

The main focus of the 2D axisymmetric finite element model was to assess the ultra-thin liner at the composite to polar boss interface. Through the initial design process it was assumed that the aluminum liner would be bonded to the composite wall and this model assessed the shear and normal stresses/strains in this region. The model also verified the initial calculations of the cylindrical wall.

Two basic load conditions were analyzed in the 2D axisymmetric finite element model. 1) An internal pressure load of 0.345 MPa (50 psig), and 2) Stresses/Strains induced by cooling the tank from ambient to 20.K (-423.F) for liquid hydrogen applications.

Finite element models were built to assess a tank design without a shear ply and a tank design with a shear ply.

Figure 3 shows the pressure loads and boundary conditions in the finite element model. The finite element analyses showed little variation in response in the cylinder section to a design with or without a shear ply. The results were consistent with the results of the classical lamination theory. The main focus of the 2D finite element model was the interaction of the ultra-thin aluminum liner in the polar boss region. Figure 5 shows a plot of maximum shear strain of the aluminum liner in the dome and polar boss region.

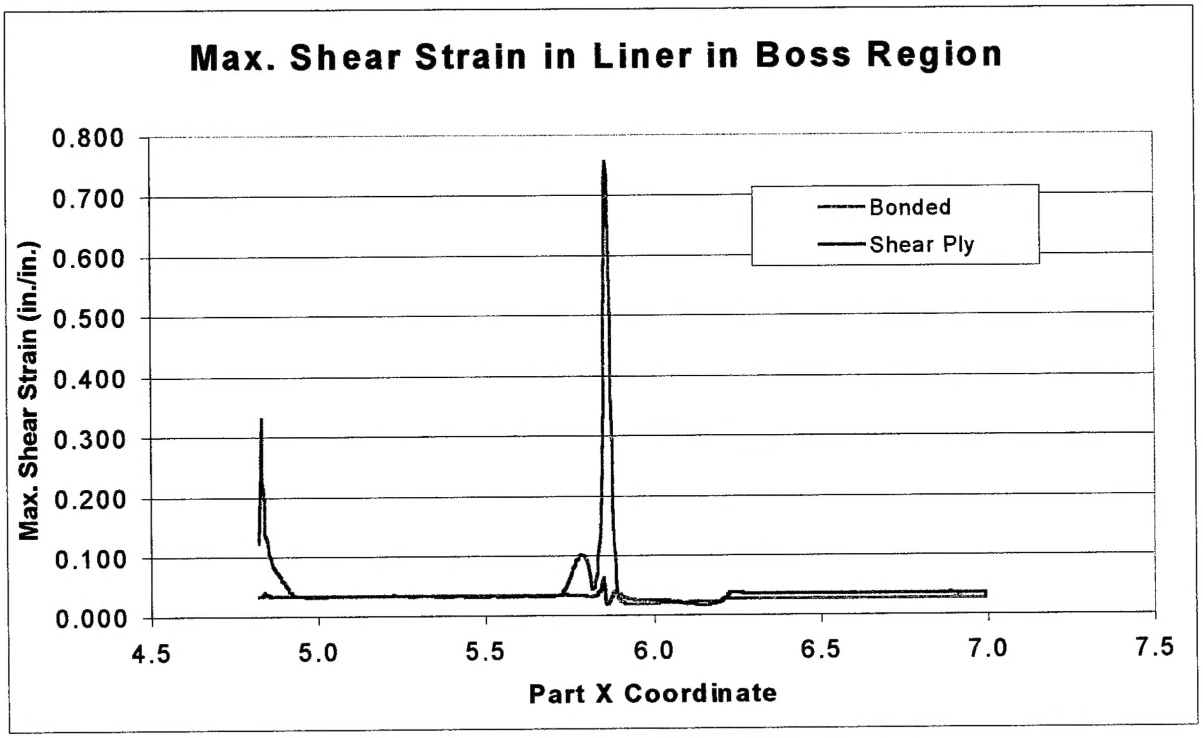

Figure 5. Liner Strain

This plot shows a high peak stress when the design does not contain a shear ply. The high peak is dramatically reduced if a shear ply is used in this region. The stress in the polar boss is also greatly reduced by adding a shear ply.

3. FABRICATION

The ultra-thin aluminum liner was fabricated using strips of aluminum foil bonded with an epoxy resin. The ends were tapered to accommodate the change in width on the domes. An epoxy adhesive was used to bond the aluminum layers together and bond the aluminum layer to the composite over wrap. It was also used to bond the aluminum liner to the polar boss. Seams were staggered and did not line up. The polar bosses were positioned on the mandrel and additional layers of aluminum were installed over the polar bosses. A shear ply was added to each boss and the composite tank wall was wrapped over the mandrel.

The polar bosses were machined from metal plate. The composite over wrap material was Toray M30S fiber impregnated with UF3339-95 TCR™ resin. The UF3339-95 resin was chosen because of the high elongation at low temperatures. The over wraps consisted of polar and hoop wraps. Figure 6 shows the composite material being wrapped onto the liner and mandrel.

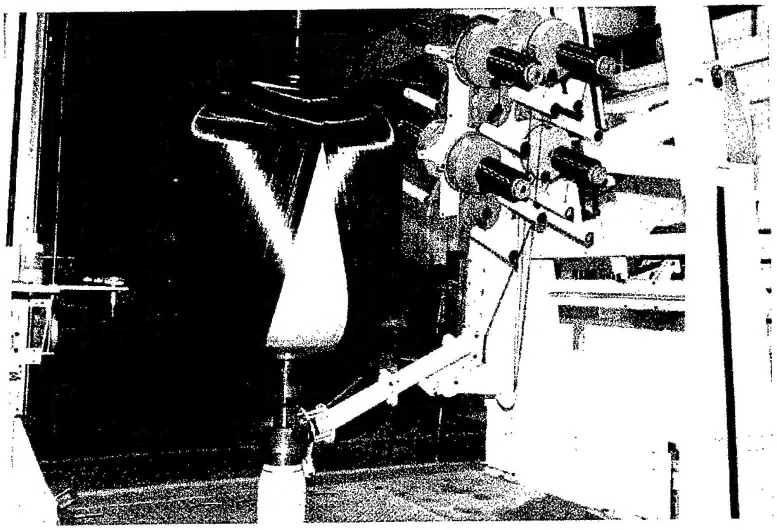

Figure 6. Composite Case Winding

4. TESTING

Testing was completed in the following sequence. 1) Pneumatic pressure test to 0.517 MPa (75 psig) with gaseous nitrogen at room temperature and leak test at 0.255 MPa (37 psig), 2) Unpressurized cold shock test with liquid nitrogen, and 3) pneumatic test to 0.517 MPa (75 psig) with gaseous nitrogen and leak test at 0.255 MPa (37 psig).

A pneumatic pressure test was performed twice on the 940 mm (37-inch) cryogenic tank. The first test was completed before the cold shock tests to demonstrate the structural strength of the tank. The second test was performed after the liquid nitrogen cold shock test to demonstrate no degradation of strength from the cold temperatures. These tests pressurized the tank to 0.517 MPa (75 psig) (1.5 X service pressure of 0.345 MPa (50 psig)) and held it for 30 seconds. The pressure in the tank was reduced to below 0.255 MPa (37 psig) for visual leak tests. In all cases, no leaks were detected. A soapy-water solution was applied to the cover plates in the seal locations was used to visually inspect the tank for leaks. The soapy-water solution bubbles and foams if a gaseous leak is present. The soapy-water solution was also applied to the composite tank in the polar boss region.

A cold shock of the tank was completed using liquid nitrogen. Liquid nitrogen was added to the tank until a liquid depth of about 127 mm (5 inches) was achieved. The tank was designed for liquid hydrogen, which is about 1/10 the density of liquid nitrogen. This depth approximates the weight of liquid hydrogen. The tank was not pressurized for the cold shock test. No leaks were observed during the cold shock test. Figure 7 shows the tank in the test position with liquid nitrogen in it. Frost is observed on the lower part of the tank. Figure 8 shows a close up view of the lower tank and polar boss.

Figure 7. Liquid Nitrogen Cryogenic Shock Test

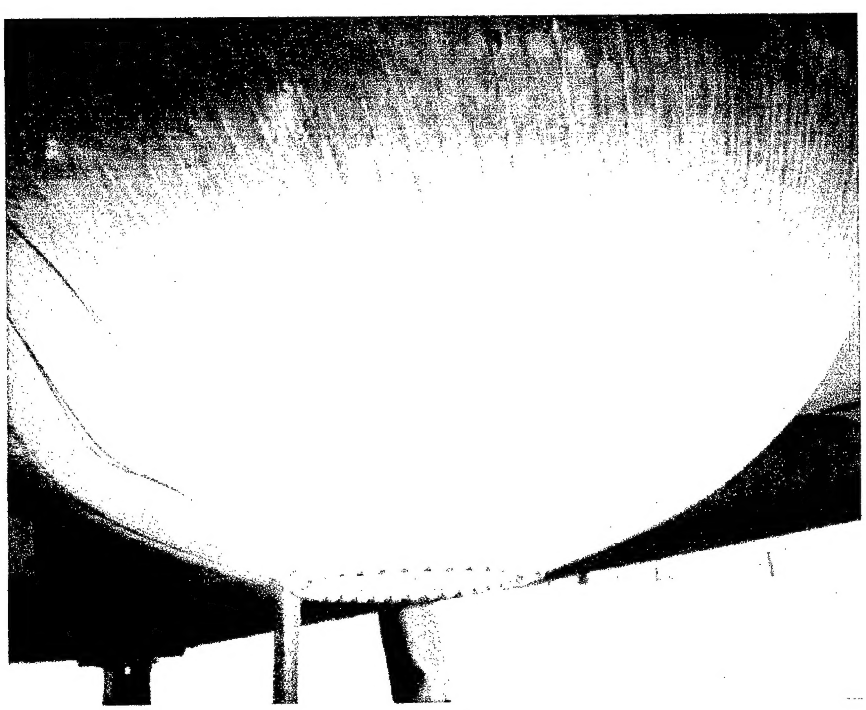

Figure 8 - Polar Boss and Cover Plate during Cold Shock Test

4. CONCLUSIONS

Thiokol has successfully designed, fabricated, and tested a 940 mm (37-inch) cryogenic tank made of M30S/UF 3339-95 TCR™ prepreg composite and metallic end closures. The bottle featured an ultra-thin aluminum liner bonded with epoxy. UF3339-95 TCR™ resin was selected for its material properties and performance at cryogenic temperatures. This tank will soon be tested with liquid hydrogen at NASA's MSFC. Thiokol has high confidence that it will hold liquid hydrogen and not leak. Future tank applications should consider composite tanks to reduce weight. In addition, methods to reduce the labor intensive layup of the laminated liner should be investigated. This will reduce the costs associated with the tank and make it more feasible for standard tanks.

A trade study was completed with two operational scale tanks to assess the merits of this technology for flight weight applications. The first tank is a composite tank with the ultra-thin aluminum liner. The second tank is an aluminum tank using 2219-T81 aluminum material. Both tanks were designed to hold 385 kg (850 lbs) of LH_2 plus 5% ullage. The trade study showed that the composite tank would weight 54 kg (118 lbs) and the aluminum tank would weigh 63 kg (139 lbs). This technology can reduce the weight for tanks required for high altitude and on orbit vehicles.

5. ACKNOWLEDGMENT

The tank was designed, fabricated and proofed under a subcontract from SRS Technologies in Huntsville, Alabama. Mr. Jim Moore is the program manager at SRS. SRS was under Air Force Research Laboratory's (AFRL) contract No. F04611-98-C-0015 with Ms. Kristi Laug, Dr. Michael Holmes, and Lt. Ivan Acosta as the program managers for AFRL.

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[1] Laug K. *The Solar Propulsion Concept is Alive and well at the Astronautics Laboratory*, (AFSC), Edwards Air Force Base, CA, JANNAF Propulsion Meeting, Cleveland OH, May 1989.

[2] Holmes M. R., "drawing provided by", Air Force Research Laboratory, Edwards Air Force Base, CA, 1999.